Practical Means for Collapse Prevention

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Introduction

- Project viability assessment
- Structural actions that provide resistance
- Detailing for resistance
- Considerations for upgrading existing buildings
- Implementation of upgrade philosophies

Dusenberry’s Definition

A major collapse that can be prevented at modest cost by prudent structural arrangements and robust details

Project Viability Assessment

- New buildings
  - Decision early in the process
  - Most systems can provide the resistance
  - Opportunities to modify the system

Project Viability Assessment

- Existing buildings
  - Often a complicated and costly endeavor
  - Existing building programming and systems limit options
  - Uncertainties concerning systems add risk

Project Viability Assessment

- Goals
- Threat evaluation
- Means to reduce exposure and threat
- Consequences of failure
- Alternatives to reduce consequences
- Measuring performance

Goals

- Save lives
- Reduce business interruption
- Reduce structural losses

Threat Evaluation

- Progressive collapse is a rare event
- Experience base is slim

Threat Evaluation

- Certain occupancies generate attention
  - Sensitive federal buildings
  - Facilities of controversial corporations
  - Facilities where large groups gather
- Certain building characteristics generate attention
  - Siting
  - Structural system
  - Contents

Threat Evaluation

- Are quantitative analyses possible?
  - Probably for some circumstances
  - For others, client or regulatory philosophy dictates

Threat Evaluation

- Consider the exposure of the facility
- Consider the vulnerability of the structure
- Consider the consequences of failure

Reducing Exposure and Threat

- Elimination of the event is far better than designing to resist the result
- Structural engineering is the back-up solution

Reducing Exposure and Threat

- Facility planning
  - Reroute traffic that might impact a structure
  - Create a barrier for oncoming traffic
  - Enhance fire protection and suppression
  - Provide stand-off distance
  - Prevent parking in the building
  - Use exterior loading dock / security station
  - Increase security / restrict access
  - Put up a “front of robustness”

Consequences

- Clients often decide without (or in spite of) detailed analyses
- Consequences are too high, even when risk is low
  - Loss of life
  - Interruption of business
  - Political consequences of a loss
- Costs often drive the decision

Alternatives to Reduce Consequences

- Reprogram the facility
  - Change locations of occupants in the building
  - Store fuels outside occupied buildings
  - Consider altering the use
  - Consider abandoning the facility

Constraints on the Decision

- Is there an inherent threat?
- Can the threat be reduced?
- Is the structural system vulnerable?
- Is there a viable way to respond?

Measuring Performance

- Need criteria that matches goals
  - Protection of occupants, contents, and business operations
  - Amount of building allowed to collapse
  - Deformation of the remaining structure
  - Repairability
  - Others

Dependent vs. Independent

- Threat dependent
  - Harden to resist initial damage
  - Determine initial damage
  - Evaluate resistance of remaining structure
- Threat independent
  - Hardening not an alternative
  - Initial damage is “arbitrary”
  - Evaluate resistance of remaining structure

Measuring Performance

- ASCE 7
  - "…[transfer] loads from any locally damaged region to adjacent regions…"
- GSA
  - Limits region of theoretical collapse when one element removed
- Indirect design
  - No measurement required

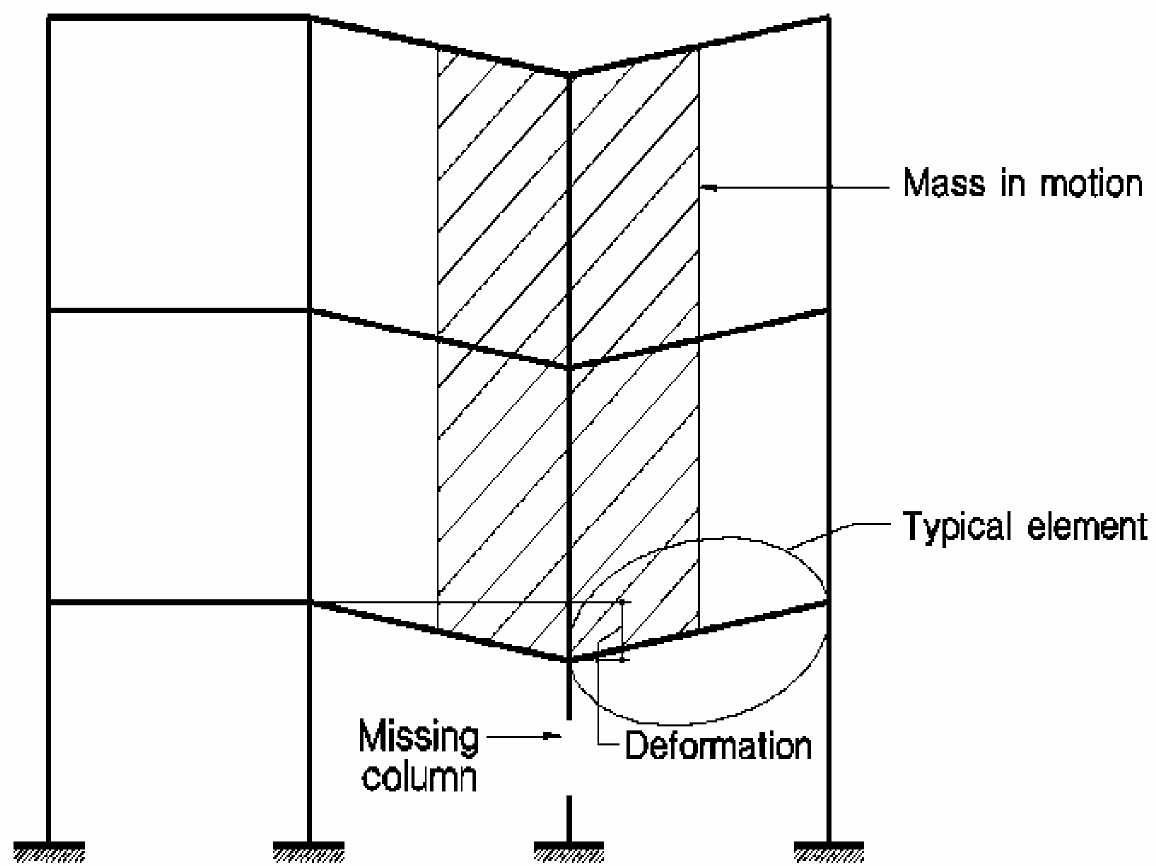
Measuring Performance

- Except for government approaches, not much guidance
- Often, performance expectation will be client driven
- Actual performance may be difficult to predict
- Advise the client

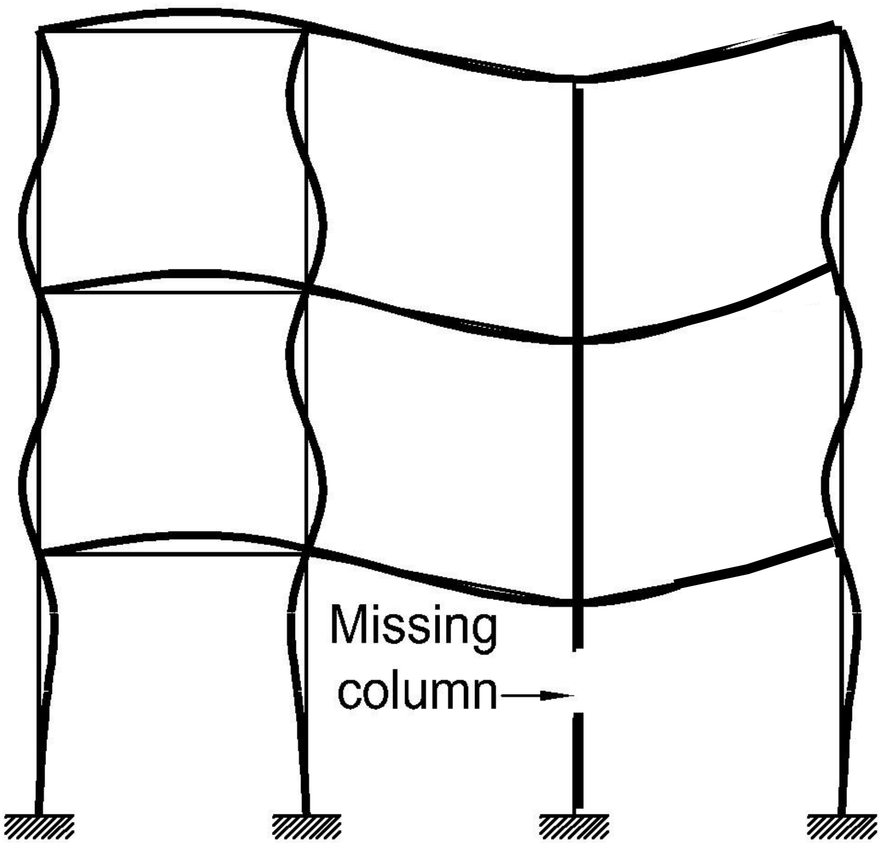
Structural Actions that Provide Resistance

- Vierendeel
- Catenary
- Arch
- Suspension

Initiating Event



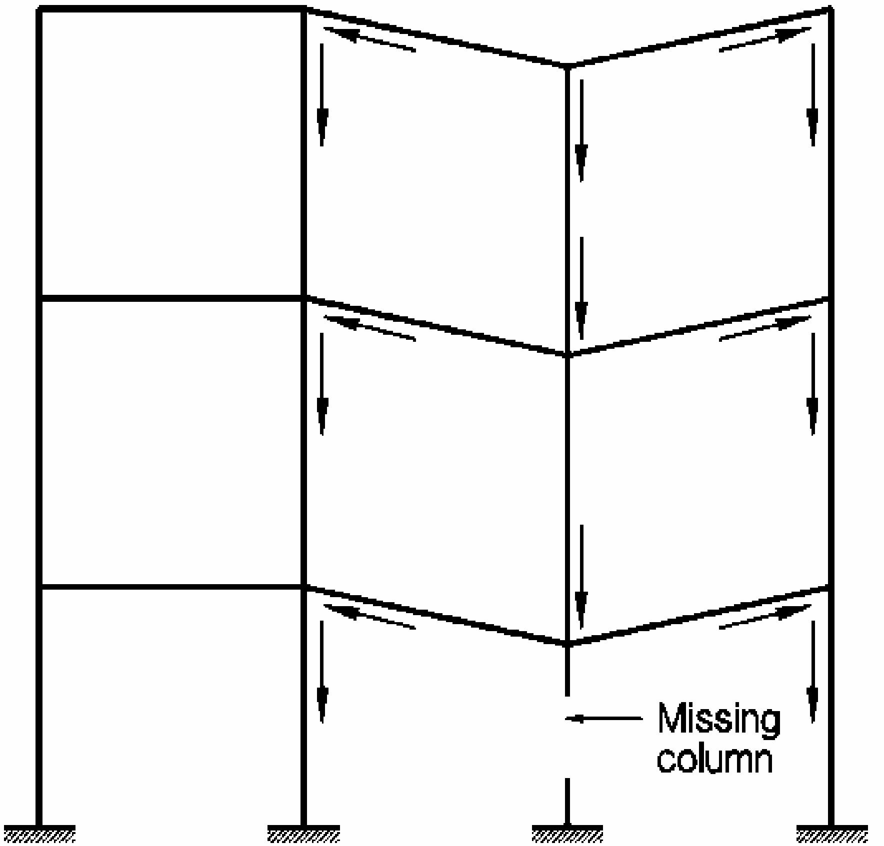
Vierendeel Action



Vierendeel Action

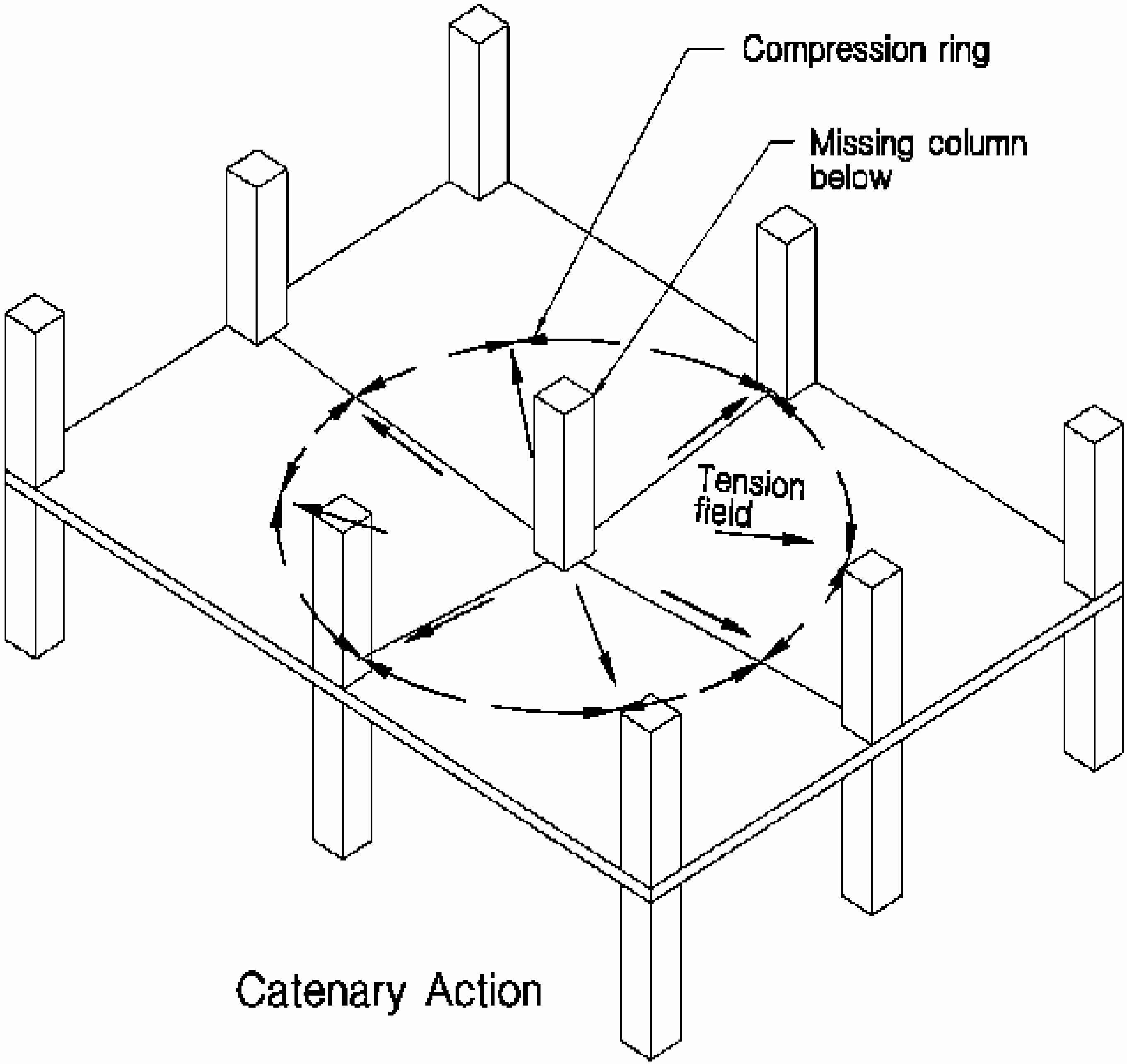
- Relies on “conventional” behaviors
- Can be implemented without major change in structural philosophy

Catenary Action

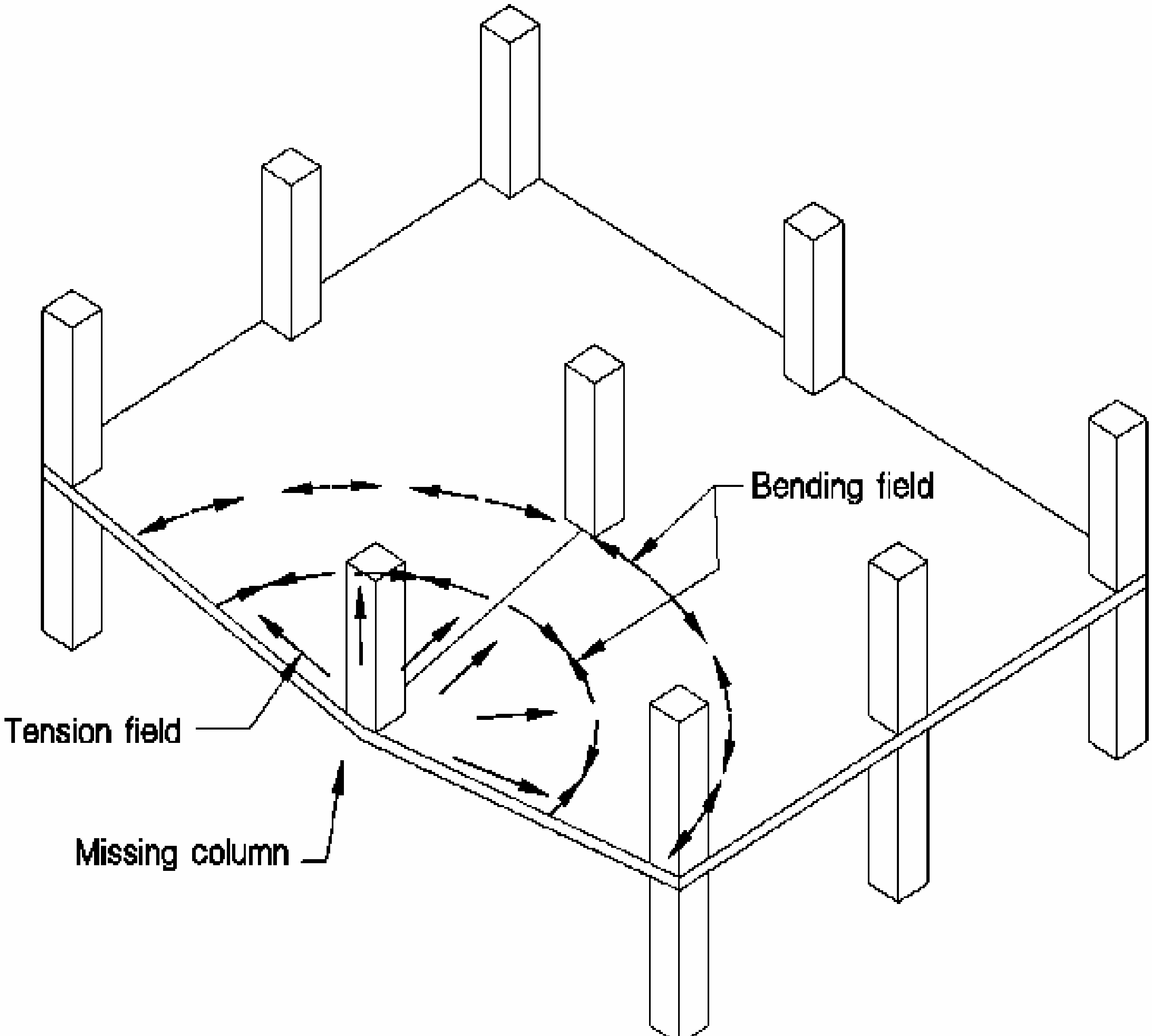


Catenary Action

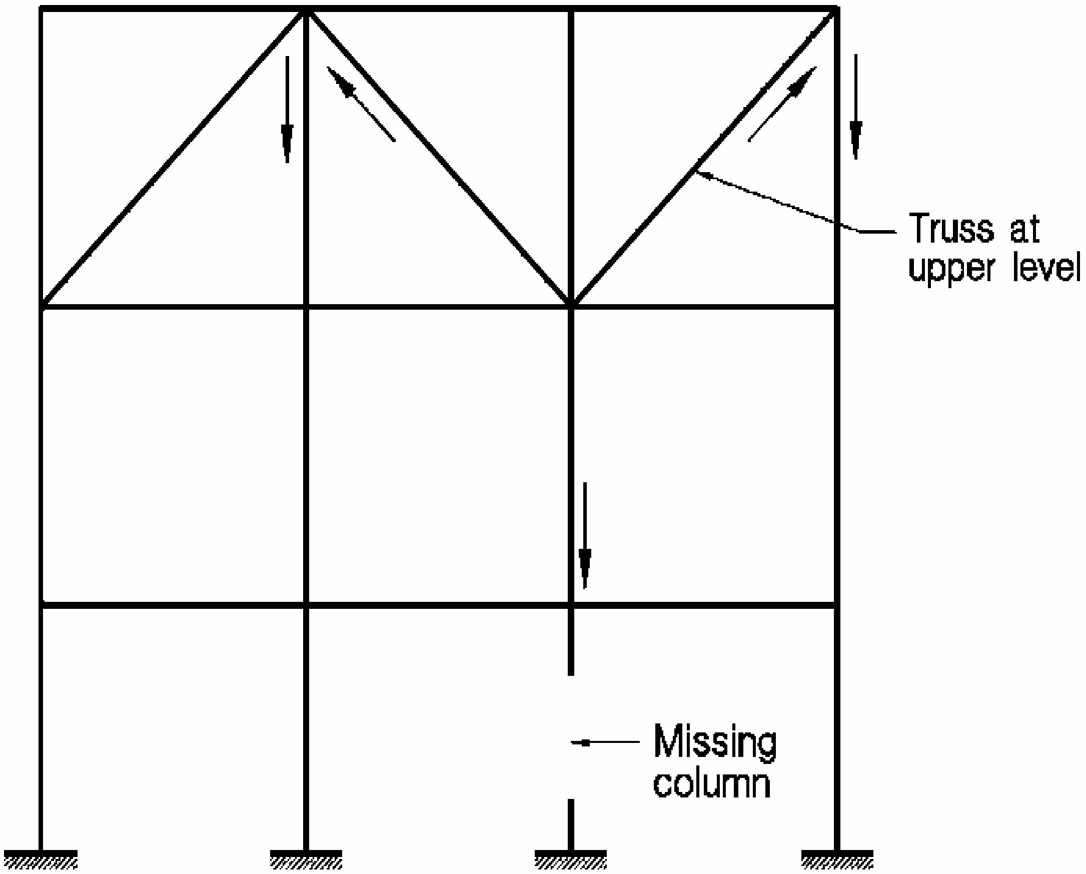
- Large deflection behavior
- Tension structure - different detailing
- Need thrust-resisting elements



Catenary Action

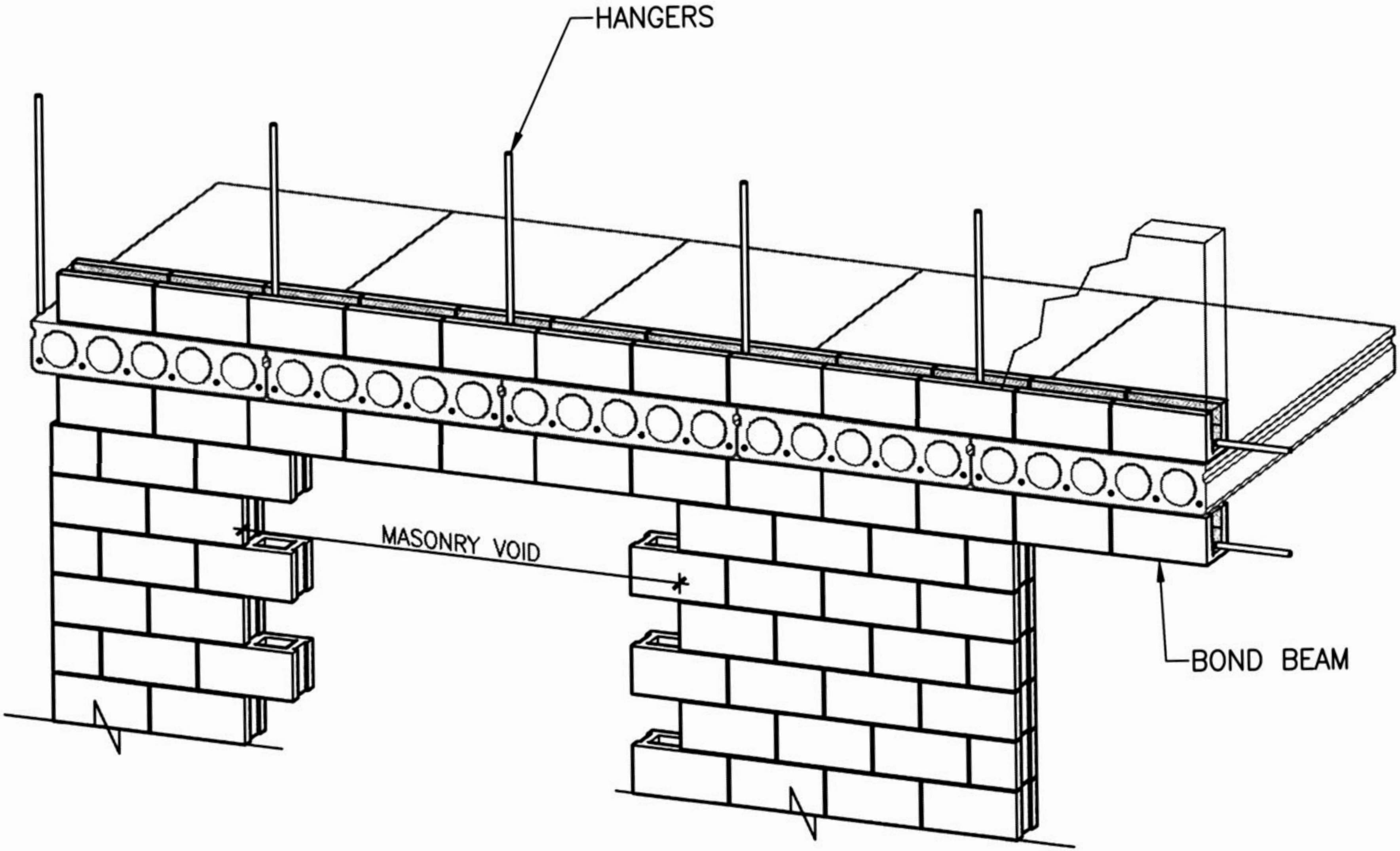

Bending field
Tension field
Missing column

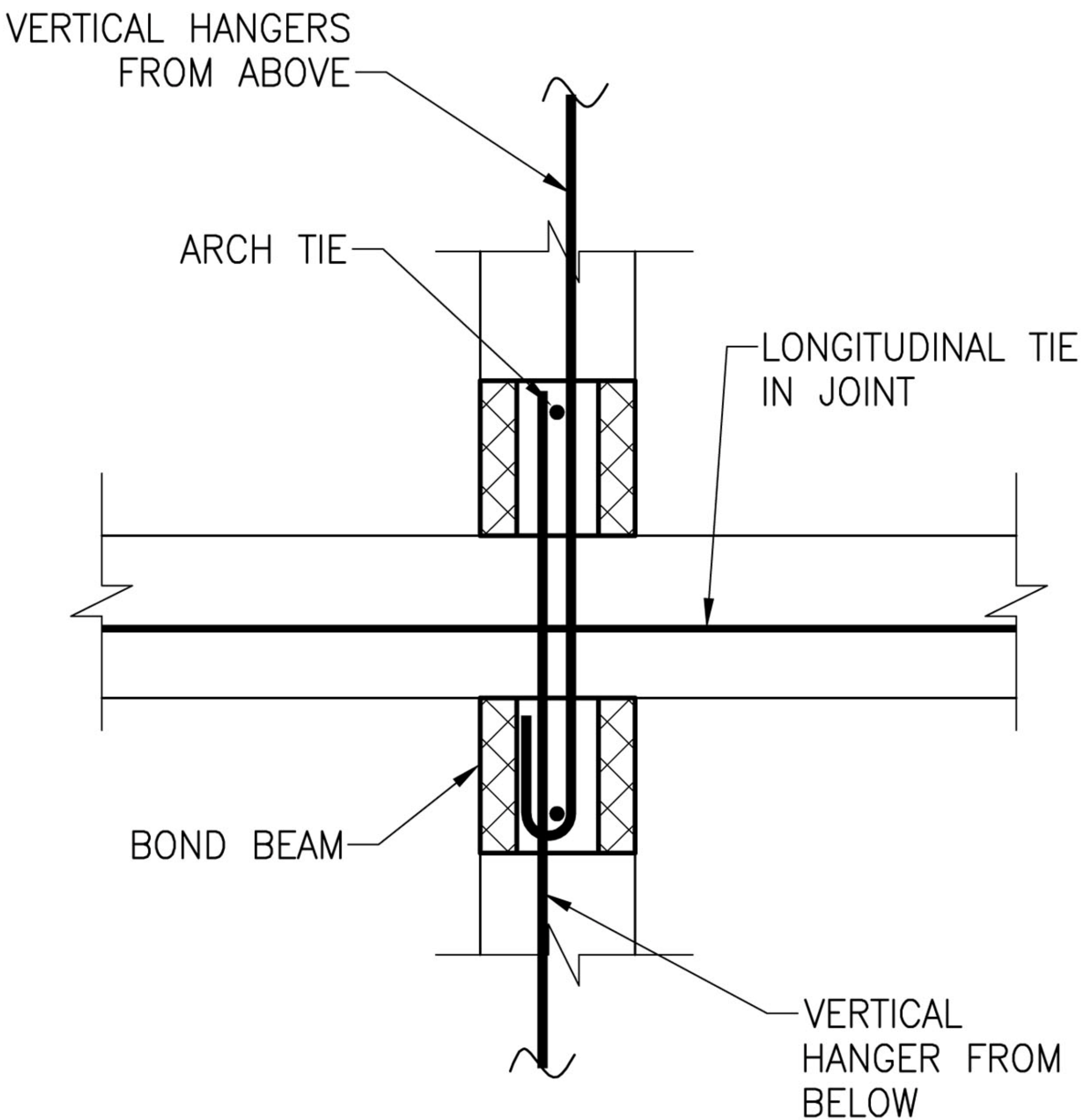
Suspension Action



Suspension Action

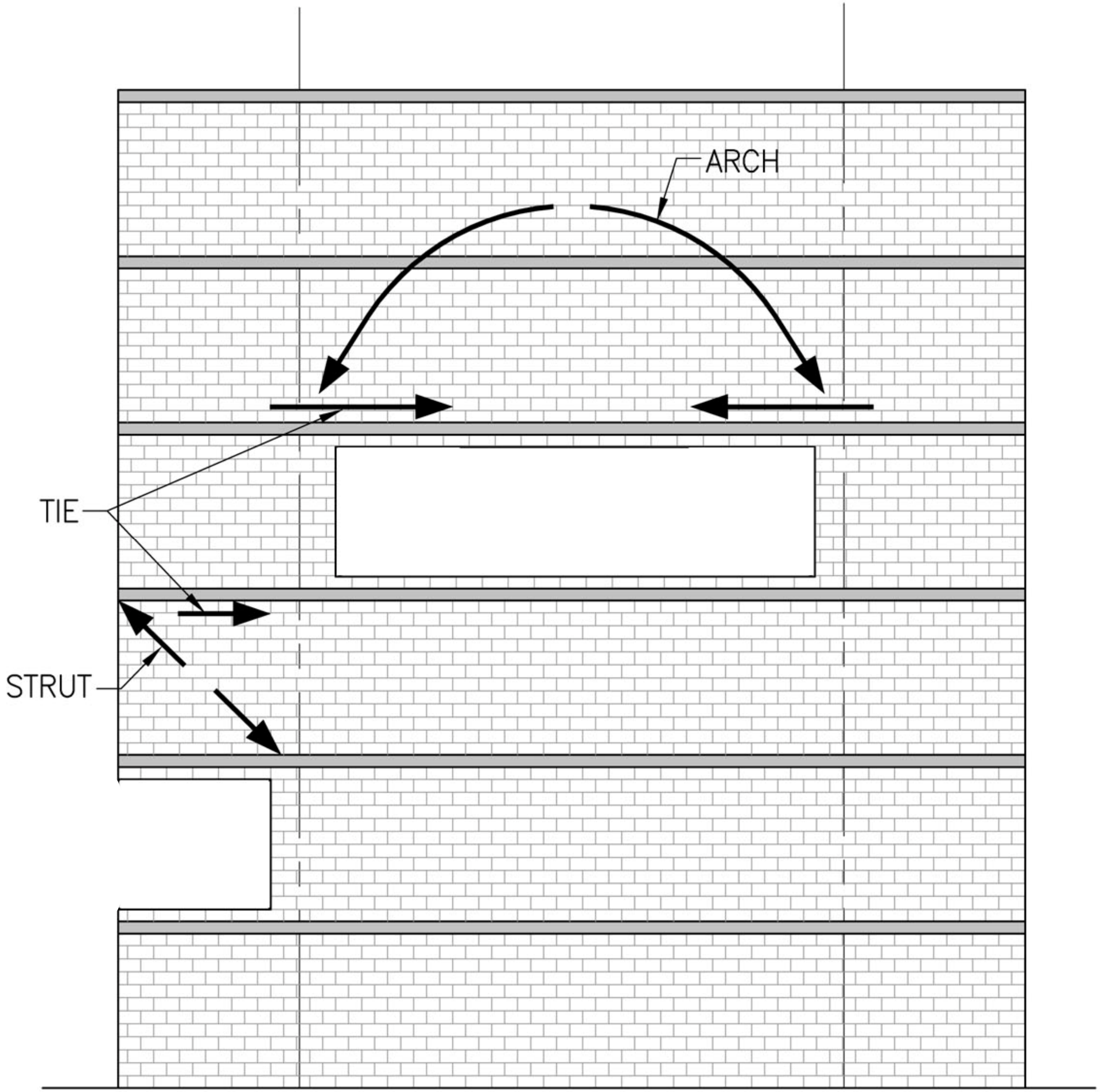
- Can be relatively small deflections
- Often requires a programming commitment to concept


HANGERS
MASONRY VOID
BOND BEAM


VERTICAL HANGERS FROM ABOVE
ARCH TIE
LONGITUDINAL TIE IN JOINT
BOND BEAM
VERTICAL HANGER FROM BELOW

Arch Action

- Bearing wall structures
- Non-structural elements


ARCH
TIE
STRUT

Detailing for Resistance

- Structural system features
- Detailing considerations

Structural System Features

- Good plan layout
  - Regular, symmetric building plan
  - Closely spaced beams framing into girders for load redistribution
  - Avoid long spans

Structural System Features

- Integrate the system
  - Engage structure in all directions
  - Multi-span beams/girders for greater continuity
  - Longitudinal spine of walls and stairwells for enhanced overall stability
  - Perpendicular walls and returns

Structural System Features

- Make the structure work for you
  - Minimize eccentricities to reduce extreme moment demand
  - Avoid discontinuities that will cause load concentrations
  - Set back perimeter columns for protection
  - Detail non-structural walls to support load

Structural System Features

- Detailing Considerations
  - Ductility
  - Force reversals
  - Ties
  - Fuses

Detailing Considerations

- Foundations
- Reinforced concrete
- Steel
- Masonry
- Precast concrete

Foundations

- Column/foundation connections need flexural capacity
- Ultimate bearing strength must support added force
- Consider wider footings
- Consider thicker footing
- Tie footings together

Reinforced Concrete

Features of RC Structures

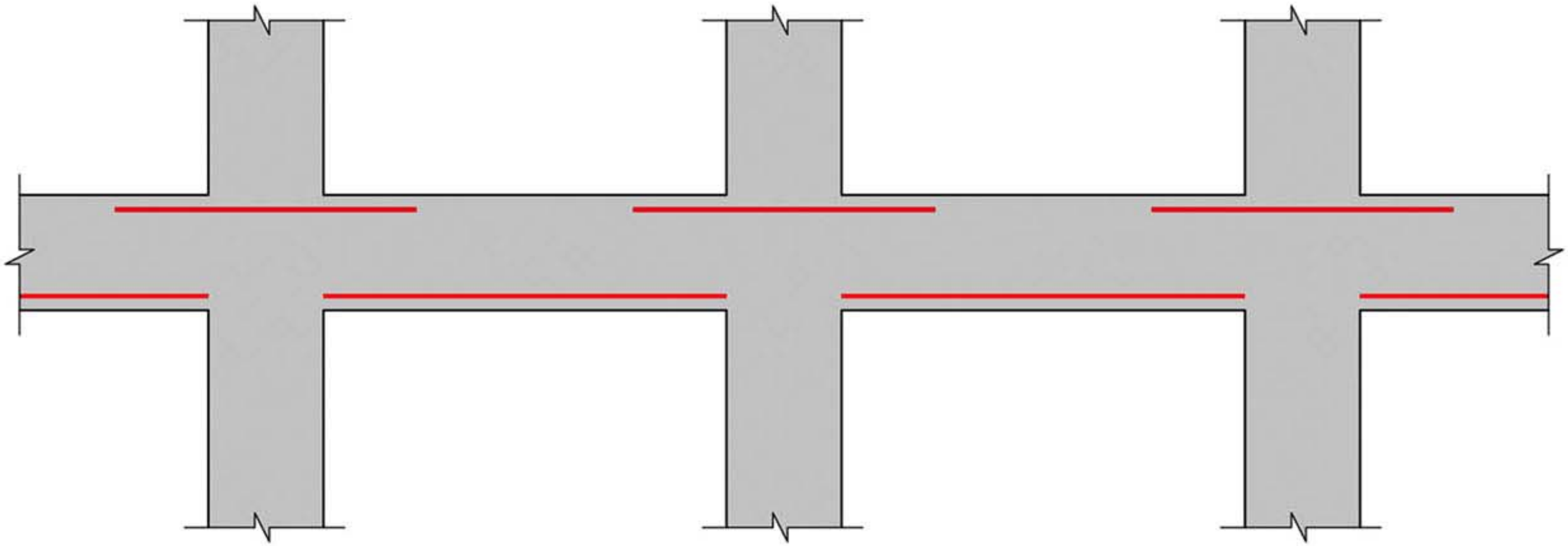
- Mass is a liability
  - But adds resistance to blast
- Members can be detailed for ductility
  - Confinement for shear resistance
  - Columns with spirals
- Can be designed for two-way action
- Can be designed for load reversals
- Can be designed for alternate paths

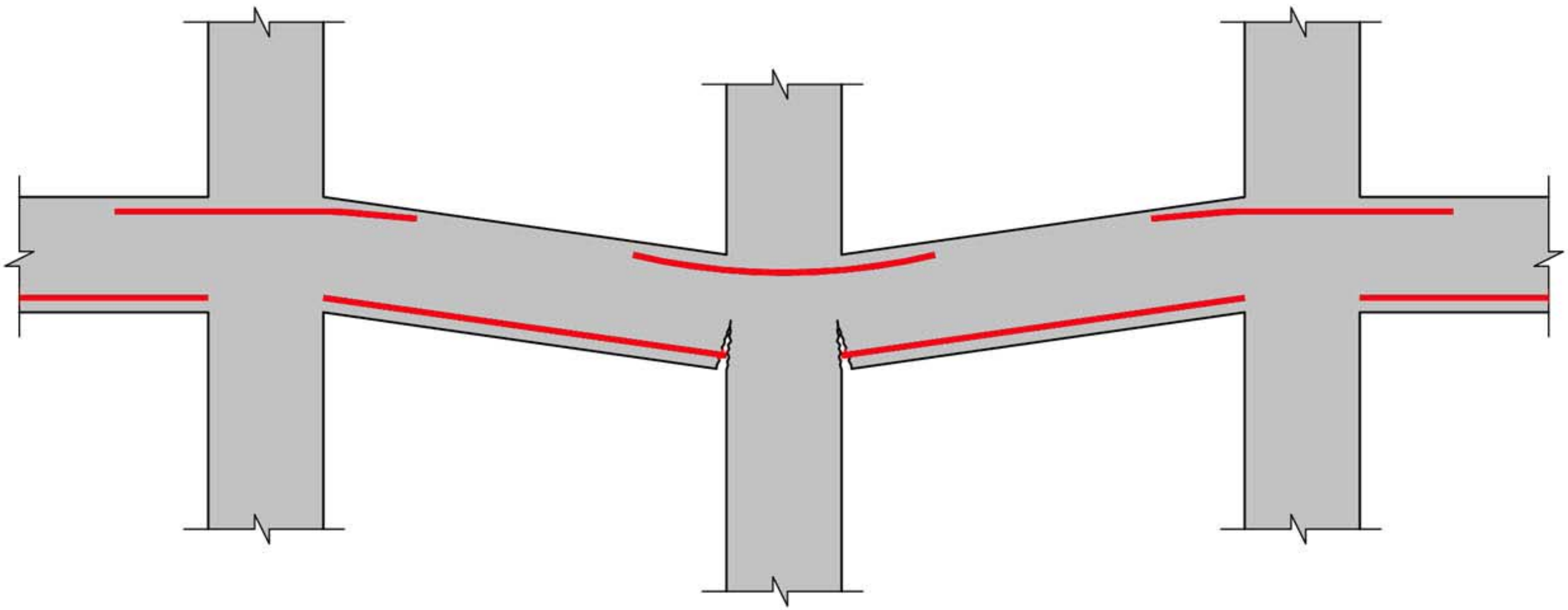
RC Beam Design

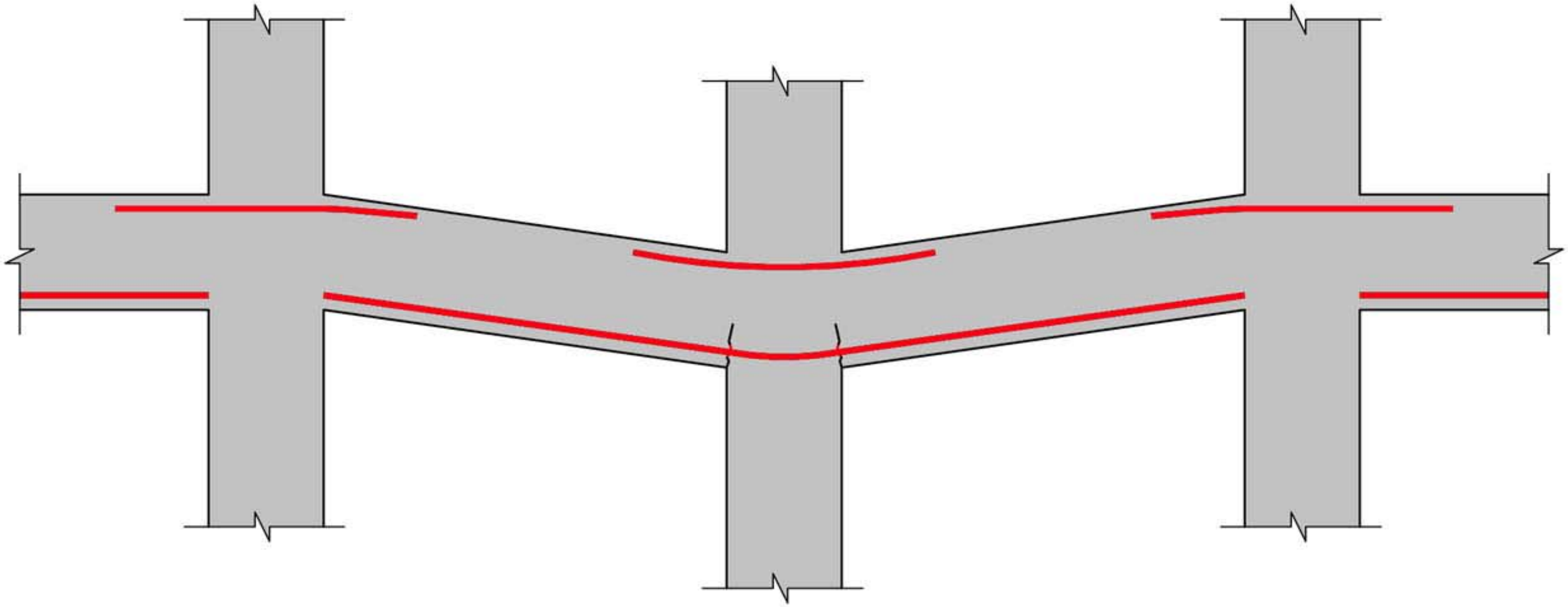
- Consider ACI 318 Chapter 21 Special Provisions for Seismic Design
  - Developed for severe cyclic loads
  - Special Moment Frame detailing dissipates energy
  - No proven correlation with collapse resistance

RC Beam Design

- Ensure flexural failure (ductile) rather than shear failure (brittle)
  - Consider very large rotations
- Maintain continuous positive and negative reinforcement







RC Beam Design

- Develop the steel
  - Use mechanical couplers that develop the ultimate strength of the bar (Type 2)
  - Do not splice reinforcement near connections or midspan
  - Use seismic hooks on all ties
  - Use seismic development lengths

RC Beam Design

- Enhance the connections
  - Provide closely spaced confining steel
    - Improves ductility
    - Increases shear and torsion strength
    - Facilitates anchorage
  - Design joint regions to be stronger than the elements
  - Design for full plastic moment capacity before shear failure

RC Beam Design

- Increase member size
  - Enhances torsional resistance
    - Need to force plastic hinge in beams: larger columns too
    - Larger columns enhance load sharing after loss of adjacent column

RC Column Design

- Provide confinement
  - Continue confining ties through joint region
- Splice column reinforcement at third-points
- Consider formation of plastic hinges, even though hinges preferred in beams

RC Slab Design

- Lightweight concrete reduces load, but performance too
- Provide continuous top and bottom reinforcement in both directions
- Do not splice at midspan or at ends
- Add reinforcing steel to tie to beams
- Cast slab monolithically with beams and girders

RC Slab Design

- Provide punching shear capacity for additional load
- Discourage flat plates: add perimeter frame
- Design for uplift

RC Wall Design

- Provide additional detailing in coupling beams and around openings
- Consider adding boundary elements to serve as columns
- Tie slab into wall

Steel Design

Steel Construction

- Ductile material
- Relatively high strength material
- Relatively light
- Connections are an issue

Steel Beam Design

- Stability
  - Provide lateral support to resist lateral-torsional buckling
  - Consider loss of slab or column on unbraced length
  - Add stiffener plates to reduce local buckling
    - To reach plastic moment in both positive and negative directions
    - Use seismically compact sections

Steel Beam Design

- Continuity
  - Use shear studs instead of deck welding to connect slab
  - Use moment connections for beams in both directions at perimeter
    - Allows beams to cantilever to spandrels
  - Two limit states:
    - Developing beam plastic moment
    - Developing beam axial tension capacity

Steel Beam Design

- Connections
  - Consider HS bolted connections to avoid brittle weld failure
  - Use notch tough weld metal recommended for seismic design
    - Specify welding according to AISC 341-02 Seismic Provisions for Structural Steel Buildings
  - Size bolted connections to prevent block shear

Steel Beam Design

- Strength
  - Composite floor system: unshored beams provide more strength than shored beams
  - Design for full plastic moment capacity before local buckling or shear failure

Steel Column Design

- Stability
  - Check stability for unbraced length with loss of adjacent beams
  - Add bracing for slender columns
  - Use seismically compact columns
  - Use concrete-filled tube columns or concrete-encased wide flanges

Steel Column Design

- Strength
  - Increased axial load for loss of adjacent columns
  - Account for moments from beams delivering their plastic moment capacities
  - Column and adjacent structure should force hinge in beam
  - Provide continuity plates so beam can develop catenary tension

Steel Column Design

- Fracture
  - For built-up column, use notch tough weld metal
  - Thick wide flange shapes should meet the special core toughness requirements

Steel Column Design

- Column splices
  - Size to develop axial tension
  - Size to permit large plastic deformations
  - Welded splices according to AISC Seismic Provisions for Structural Steel Buildings
  - Use notch tough weld metal

Slab Design with Steel Framing

- Strength
  - Lightweight concrete floor slabs will reduce load at a cost in performance
  - Provide additional reinforcing steel: bars in both directions rather than WWF
  - Place reinforcement in slab center or use two layers of continuous bars
  - Reinforce slab to carry self-weight during loss of column or beam

Slab Design with Steel Framing

- Continuity
  - Slab on metal deck can provide lateral support to beams
  - Use shear studs rather than puddle welds to connect to beams
  - Lap reinforcement for continuity
  - Do not use mechanical splices unless well staggered

Masonry

Reinforced Masonry

- Strength
  - Strengthen diaphragm for membrane behavior
  - Provide continuous steel in both directions
    - Provide at least one horizontal bar along each course and one vertical bar in each cell
    - Use fully-grouted construction
  - Consider reinforcing walls to span over areas of damage

Reinforced Masonry

- Continuity
  - Tie diaphragm to walls for out-of-plane forces
  - Use lap splices or Type 2 mechanical couplers
  - Dowel wall into foundation

Unreinforced Masonry

- Avoid
- Limit height to one story
- Provide separate independent pilasters or columns for gravity load

Precast Construction

Precast Floor Systems

- Connections are an issue:
  - Provide ductile steel plate connections
  - Integrate with reinforcement
  - Use slotted holes for service conditions
- Provide mild steel top and bottom for force reversals
- Provide topping slab, reinforced accordingly
  - Mechanically connect to members

Tilt-up Construction

- Strength
  - Place first line of interior columns close to panels
  - Design framing to cantilever from first interior column
  - Design cast-in-place pilasters as columns
  - Design roof edge to span over at least one missing panel

Tilt-up Construction

- Continuity
  - Provide membrane capacity in diaphragm
  - Tie diaphragm to walls
  - Tie panels together with mechanical connections or cast-in-place pilasters
  - Tie walls to foundation

Post-tensioned Construction

- Unbonded construction is an issue
- Provide mild reinforcement for gravity loads
  - Especially at perimeter
  - Provide continuous mild reinforcement in top and bottom of floors
  - Design post-tensioning for live load only
- Interconnect elements with ductile connections

Considerations for Upgrading Existing Buildings

- Constrained by as-built construction
  - Detailing will not be ideal for PC resistance
  - Connections will not provide ductility
  - Detailing will not be verified by test or analyses
  - Building programming will be fixed
- Uncertain as-built conditions
- Uncertain materials

Considerations for Upgrading Existing Buildings

- Buildings with effective seismic design are candidates
- When conditions complicate:
  - Remove the threat
  - Upgrade vulnerable elements
  - Add interstitial construction
  - Avoid the need for collapse resistance

Evaluation of Existing Systems

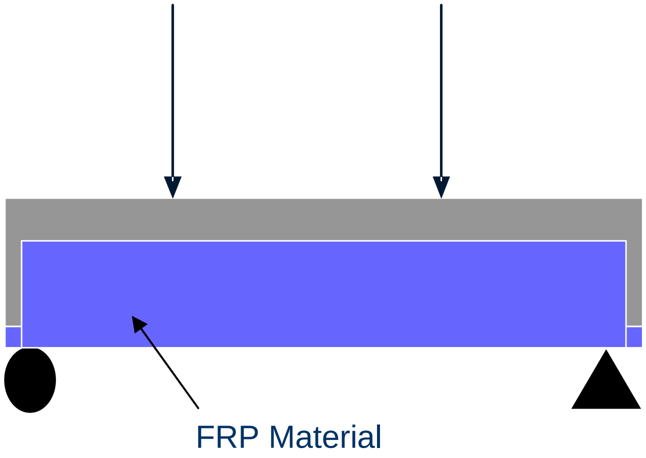
- Review documentation
- Verify as-built construction
- Materials studies
- Evaluation of detailing

Concrete and Masonry Structures

- Usually involves encapsulating elements
  - Difficult to be certain about construction
  - Difficult to add ductility to existing elements
- Upgrades often involve:
  - FRP or steel jackets
  - Encasement with more RC concrete
  - Addition of new elements
    - Cables, ties, interstitial elements

(a)

(b)



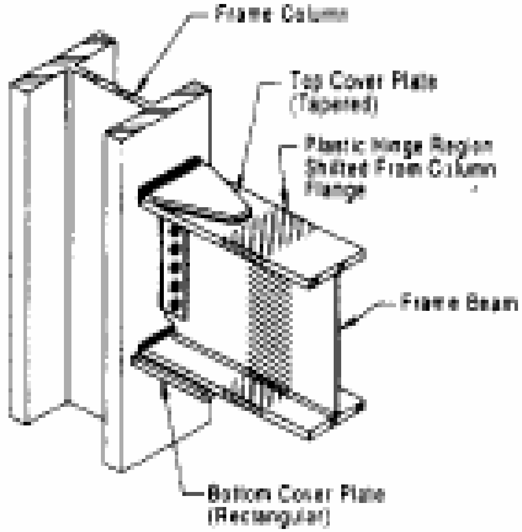
(c)

(a) and (b): Taghdi et al., 2000

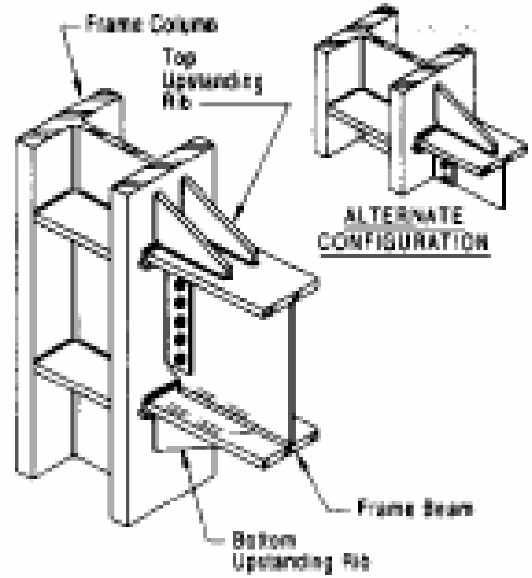
Mosallam, 2000

Steel Structures

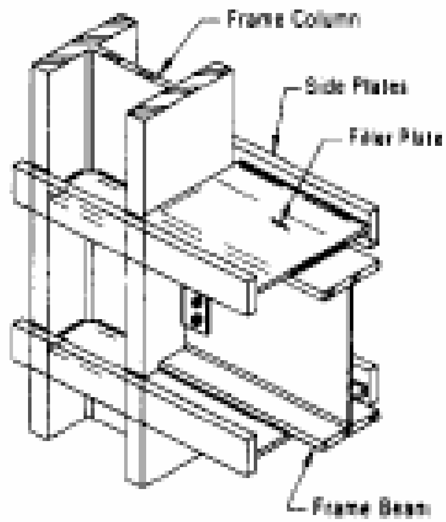
- Easier to upgrade than RC structures
- Connections often are the problem
- Engaging slab in resistance is a problem
- Upgrades can mimic details with tested behavior



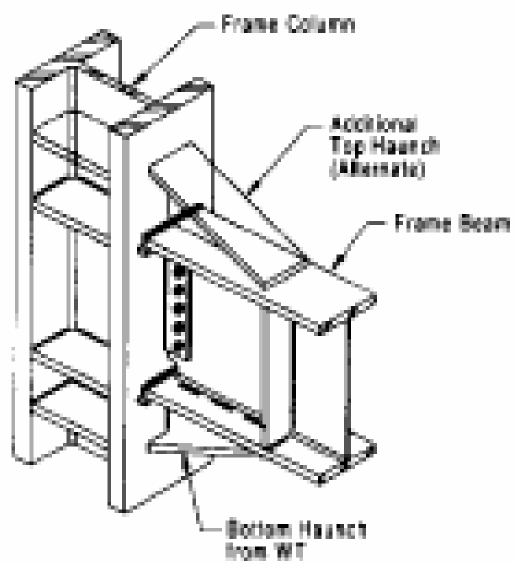
(a) Coverplate



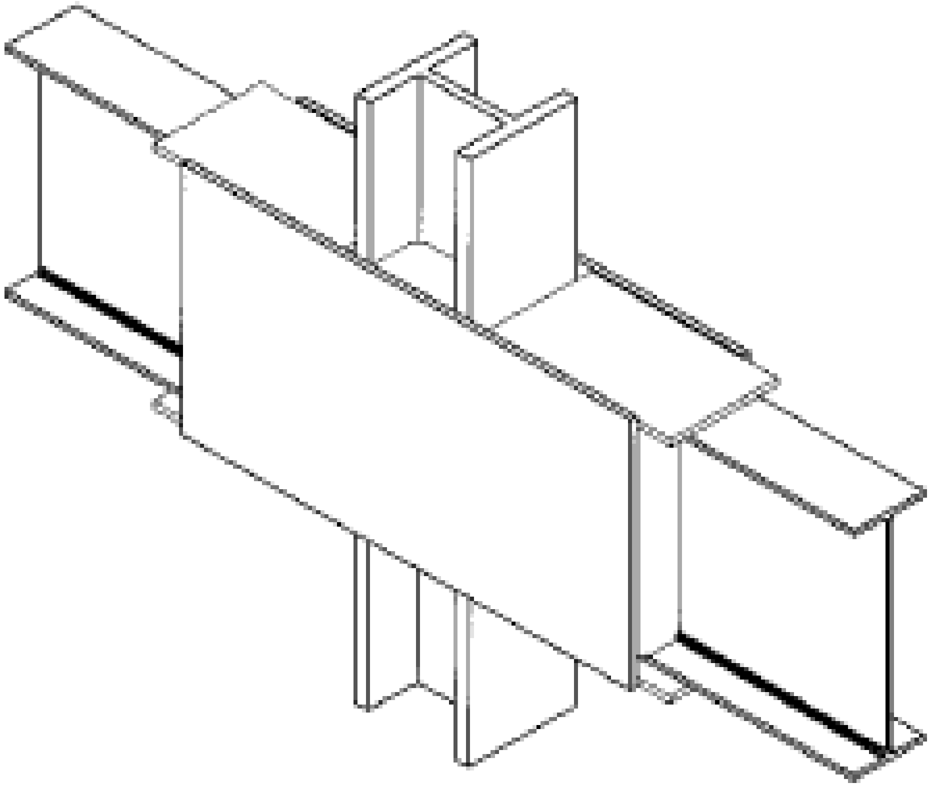
(b) Upstanding Rib



(c) Side Plate



(d) Haunch



SidePlate™

Implementation Summary

- Evaluate the threat
- Consider means to reduce the threat
- Study options for reprogramming the facility
- Develop performance expectations
- Evaluate upgrade methods
- Assign costs (direct and indirect)
- Discuss and revise with client
- Design